AFOSR-TR- 79-1325

LEVEL II

George K. Serovy
Patrick Kavanagh
Theodore H. Okiishi
Elmer C. Hansen
November 1979

ADA079617

AERODYNAMICS OF ADVANCED
AXIAL-FLOW TURBOMACHINERY

Annual Report
1 October 1978 - 30 September 1979

D D C

JAN 21 1980

RECEIVED

D

TURBOMACHINERY
COMPONENTS RESEARCH PROGRAM

ISU-ERI-Ames-80080
TCRL-14
Projects 1382-1386

ENGINEERING RESEARCH INSTITUTE
IOWA STATE UNIVERSITY
AMES, IOWA 50010 USA

80   1 16 066

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
AFOSR TR-79-1325		

4. TITLE (and Subtitle)	5. TYPE OF REPORT & PERIOD COVERED
AERODYNAMICS OF ADVANCED AXIAL-FLOW TURBOMACHINERY.	INTERIM 1 Oct 78 - 30 Sep 79
	6. PERFORMING ORG. REPORT NUMBER TCRL-14/ISU-ERI-Ames-80060

7. AUTHOR(s)	8. CONTRACT OR GRANT NUMBER(s)
GEORGE K. SEROVY, ELMER C. HANSEN PATRICK KAVANAGH THEODORE H. OKIISHI	F49620-79-C-0002

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
IOWA STATE UNIVERSITY ENGINEERING RESEARCH INSTITUTE AMES, IOWA 50011	2307A4 61102F

11. CONTROLLING OFFICE NAME AND ADDRESS	12. REPORT DATE
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BLDG 410 BOLLING AIR FORCE BASE, D C 20332	Nov 79
	13. NUMBER OF PAGES 53

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report)
	UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

AXIAL-FLOW TURBOMACHINERY	CASCADE FLOW
AXIAL-FLOW COMPRESSOR	COMPUTATIONAL FLUID MECHANICS
AXIAL-FLOW TURBINE	PERIODICALLY UNSTEADY FLOW
	TURBOMACHINE FLOW MEASUREMENT

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
A multi-task research program on aerodynamic problems in advanced axial-flow turbomachine configurations is being carried on at Iowa State University. The elements of this program are intended to contribute directly to the improvement of compressor, fan, and turbine design methods. Experimental efforts in intra-passage flow pattern measurement, unsteady blade row interaction, and control of secondary flow are included, along with computational work on inviscid-viscous interaction blade passage flow techniques. This first Annual Report summarizes progress to date and indicates the direction of each task for the immediate future.

DD FORM 1473 EDITION OF 1 NOV 65 IS OBSOLETE   Unclassified

ENGINEERING RESEARCH

ENGINEERING RESEARCH

ENGINEERING RESEARCH

ENGINEERING RESEARCH

ENGINEERING RESEARCH

Accession For	
NTIS GRA&I	☒
DDC TAB	
Unannounced	
Justification	
By	
Distribution/	
Availability Codes	
Dist.	Avail and/or special
A	

**AERODYNAMICS OF ADVANCED
AXIAL-FLOW TURBOMACHINERY**

Annual Report
1 October 1978 - 30 September 1979

George K. Serovy
Patrick Kavanagh
Theodore H. Okiishi
Elmer C. Hansen
November 1979

AIR
NO
Th   (AFSC)
a:
D   d is
A.   (7b).
Technical Information Officer

**TURBOMACHINERY COMPONENTS RESEARCH LABORATORY
DEPARTMENT OF MECHANICAL ENGINEERING
ENGINEERING RESEARCH INSTITUTE
IOWA STATE UNIVERSITY   AMES, IOWA 50011**

TABLE OF CONTENTS

SECTION I

INTRODUCTION

During the past twenty years a coordinated program of research on
problems related to the fluid dynamics of axial-flow turbomachinery has
been developed at Iowa State University in the Turbomachinery Components
Research Laboratory. Numerous projects funded by the National Aeronautics
and Space Administration (NASA), the United States Air Force Office of
Scientific Research (USAF/AFOSR), the United States Air Force Aero
Propulsion Laboratory (USAF/AFAPL), the Naval Air Systems Command, and
other government and industrial organizations have been completed.
Beginning 1 October 1978, the Iowa State University Department of Mechani-
cal Engineering faculty involved with turbomachinery research were
funded through AFOSR Contract F49620-79-C-0002 to develop a multi-task
program concentrating on problems in the aerodynamics of advanced axial-
flow compressors, fans, and turbines. Five projects were scheduled
during the initial two-year contract period.

> Task I: Analytical and Experimental Investigation of Intra-
> passage Flow in a Constant Mean Radius Rectangular
> Cross-Section Passage Representative of Passages in
> Turbomachinery

> Task II: Evaluation and Management of Unsteady Flow Effects in
> Axial-Flow Compressors

> Task III: Development of a Design-System Oriented Deviation
> Angle Prediction Equation for Advanced Compressor and
> Fan Configurations

1

Task IV: Experimental Study of Merits of Specific Flow Path

            Geometry Changes in Controlling Secondary Flows in

            Axial-Flow Compressors

Task V: Definition of Experimental Programs and Facilities

            Appropriate for University Turbomachinery Research

            Programs

All projects, except for Task V, were actively pursued during the
first year of the contract period. Task V was scheduled and budgeted
for the year beginning 1 October 1979 and has now been initiated. Indi-
vidual summaries of the results achieved in each area of the investiga-
tion are included in the following section.

SECTION II

STATUS OF THE RESEARCH PROGRAM

Each of the five projects in the contract program is discussed in
this section. Task I originated in internally-supported work at Iowa
State University and is based on earlier analyses carried out with support
from the Pratt & Whitney Group of the United Technologies Corporation.
Task II is a continuation of research funded by AFOSR since 1975. Task
III continues computation and analysis initiated in 1974 with funding
from NASA and extended under an AFOSR grant in 1978. Task IV evolved
from discussions with Dr. Arthur J. Wennerstrom of AFAPL, and is intended
to result in fundamental design data that will be usable in future high-
efficiency multistage axial-flow compressor development.

1. TASK I: ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF INTRAPASSAGE
   FLOW IN A CONSTANT MEAN RADIUS RECTANGULAR CROSS-SECTION PASSAGE
   REPRESENTATIVE OF PASSAGES IN TURBOMACHINERY

The test rig for the experimental portion of Task I, a curved rec-
tangular cross-section passage and associated hardware, has been designed
and is partly fabricated at this time. Completion of the test rig and
the start of the preliminary testing and flow visualization experiments
are expected in January, 1980. As originally planned, the large, low-
speed air flow test loop in the Turbomachinery Laboratory will be used
to carry out the testing program. A diagram of the test arrangement
identifying particular components is shown in Figure 1.

A convergent flow nozzle was designed, built, and installed as a
reentrant nozzle in the discharge port of the flow loop plenum. The
nozzle was constructed of laminated mahogany. The nozzle has a 0.508-m
diameter throat and an elliptic cross section over the innermost portion

BOUNDARY LAYER GENERATOR SECTION

ADAPTOR SECTION

0.533 m (PASSAGE MEAN RADIUS)

CURVED PASSAGE AND DISCHARGE TEST SECTION

SLIDEBAR TRAVERSE STATIONS (12)

SIDEWALL

SIDEWALL

0.229 m

0.762 m

1.04 m

TRANSITION SECTION

SIDEWALL BLEED PORT

AIRFLOW

TOP VIEW

TOP METAL ENDWALL

0.406 m

BOTTOM PLEXIGLASS ENDWALL
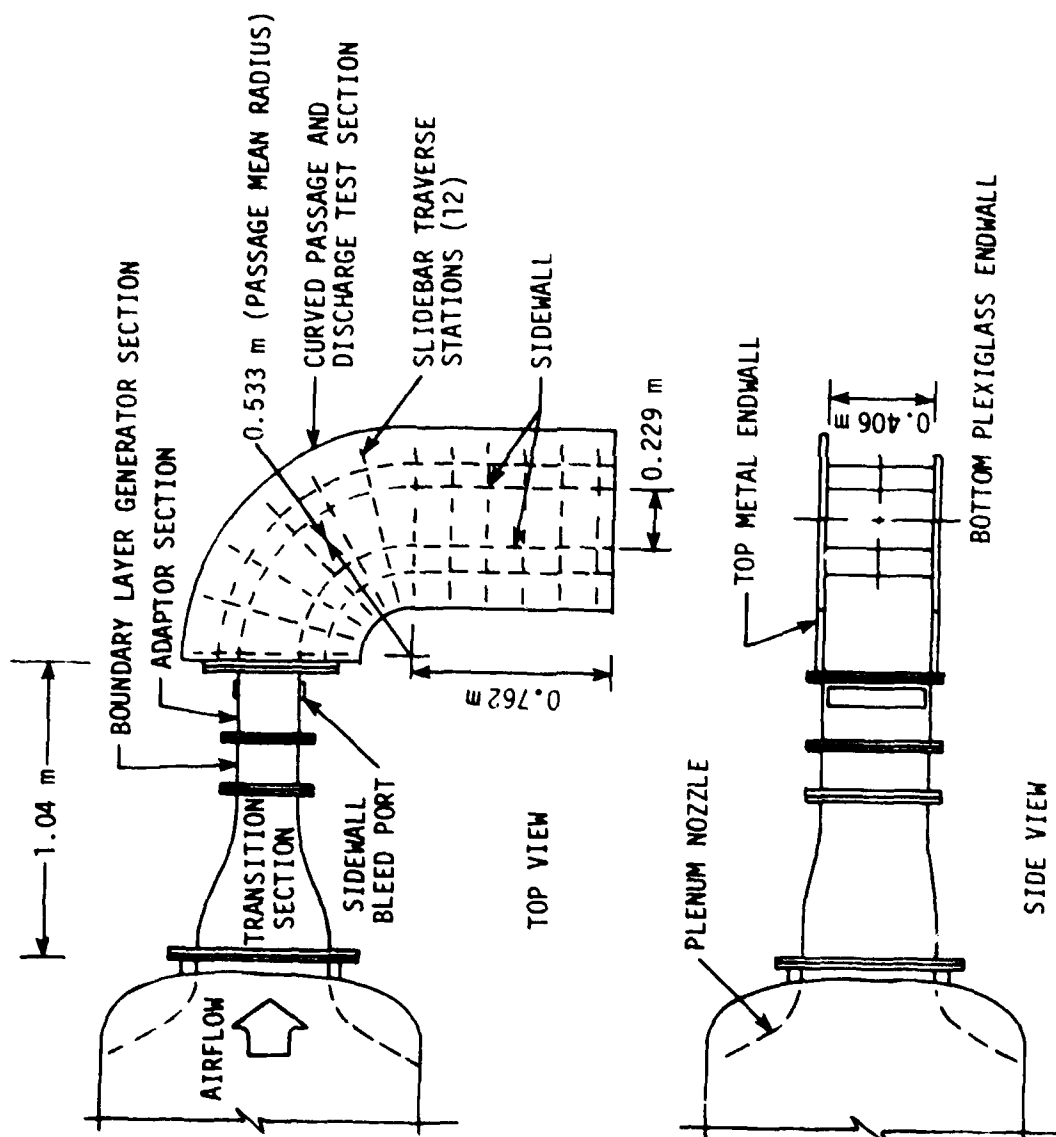
PLENUM NOZZLE

SIDE VIEW

Figure 1. Schematic Diagram of Experimental Passage Rig, Task 1.

of the nozzle to provide a smoothly accelerated flow to the transition section immediately downstream. The outer portion of the nozzle has a straight conical section. The transition section (from circular to rectangular cross section) was fabricated from a blown mixture of fiber-glass filament pieces and resin and then molded to a steel circular mounting ring. A rectangular flange downstream was attached after the transition section had been formed. A unique scheme described by Eichhorn and Fox [Ref. 1] was employed in molding the transition section over a water-inflated rubber diaphragm to produce a smoothly varying transition from the circular to rectangular cross section. Testing of the transition section will be carried out to determine flow uniformity at the discharge.

The sections downstream of the transition section are the boundary layer generator section, adaptor section, and the test section proper. These sections all have uniform passage cross section of 0.229 m by 0.406 m. The boundary layer generator section employs slanted, uniform-mesh screens to produce thick two-dimensional boundary layers along either endwall of the test section. The adaptor section serves to adjust the flow into the test section. This section contains bleed doors which can be adjusted to remove boundary layers that may form on the vertical sidewalls of the passage. The boundary layer generator and adaptor sections are fabricated from 13 and 19-mm thick plexiglass plate. Flow testing of these sections and adjustment of the screens and bleed doors to obtain the thick boundary layer behavior desired in the testing program will commence in December, 1979.

5

The test section consisting of the 90-degree bend and straight discharge portion is presently under fabrication. The upper endwall is being machined from 19-mm thick aluminum tooling plate. This endwall contains 12 traverse slots across the flow passage and at various sta ons in the flow through the test section. Brass tooling bar stock (9.525 mm by 19.050 mm) is to be used for slide bars in these slots and will be precisely fitted in the endwall to produce a smooth inner wall of the passage. The slide bars carry five-hole directional and static pressure tap probes used in mapping out details of the flow at each traverse station. The sidewalls of the test section are being machined from laminated mahogany pieces and will contain permanent static pressure taps at 25-mm vertical intervals at each traverse station. Finally, the lower endwall is made of 19-mm thick plexiglass plate for flow visualization and is attached to the test section by quick-release bolts and mounting brackets for easy access to the flow passage.

Overall construction of the test rig is estimated to be about 70 to 75 percent completed; completion is expected by the end of December, 1979. Assembly of the test rig, its installation in the flow loop, and installation of the five-hole probe and probe positioner will be completed in January, 1980. Some delays have been caused by late delivery of materials and by modifications or redesign of some components due to size limitations and difficulties in machining.

The data acquisition and experiment control system for Task I has been assembled and has been used in calibrating five-hole directional pressure probes (United Sensor DC-125) for the testing program. This

system, which is a permanent installation in the Turbomachinery Laboratory for the low-speed air flow loop, is shown in Figure 2.

The controller for the system is a 32K Commodore PET computer. The PET has IEEE-488 capability, making it compatible with the multimeter (HP 3490) and the scanner (HP 3495). An actuator card (option 002) is employed with the scanner.

In addition to the CRT display on the PET, hard copy can be written out on a Digital Corporation Decwriter through use of an RS232 serial adaptor.

In operating the data acquisition and experimental control system, the multimeter can be put in any one of its modes and triggered on command by the PET. Once triggered, the multimeter outputs a measurement to be read and then stored or reduced by the PET. The multimeter presently in use in the system (HP 3490) must be shared with other teaching and research projects in the department. Consequently, to avoid inconvenient downtime and other delays in testing, a dedicated faster and more advanced multimeter (HP 3455) has been purchased for the data acquisition system. Delivery of the new multimeter is expected early in 1980.

The PET also communicates with the scanner in the system to select on command any one of ten single-throw double-pole channels. The use of these channels allows Scanivalve port selection, probe positioner control and position feedback, and connection to the amplifier (Endevco Model 4476.2) and filter (General Radio 1952 Universal Filter) for pressure measurement. A Druck Model PDCR22 pressure transducer with a range
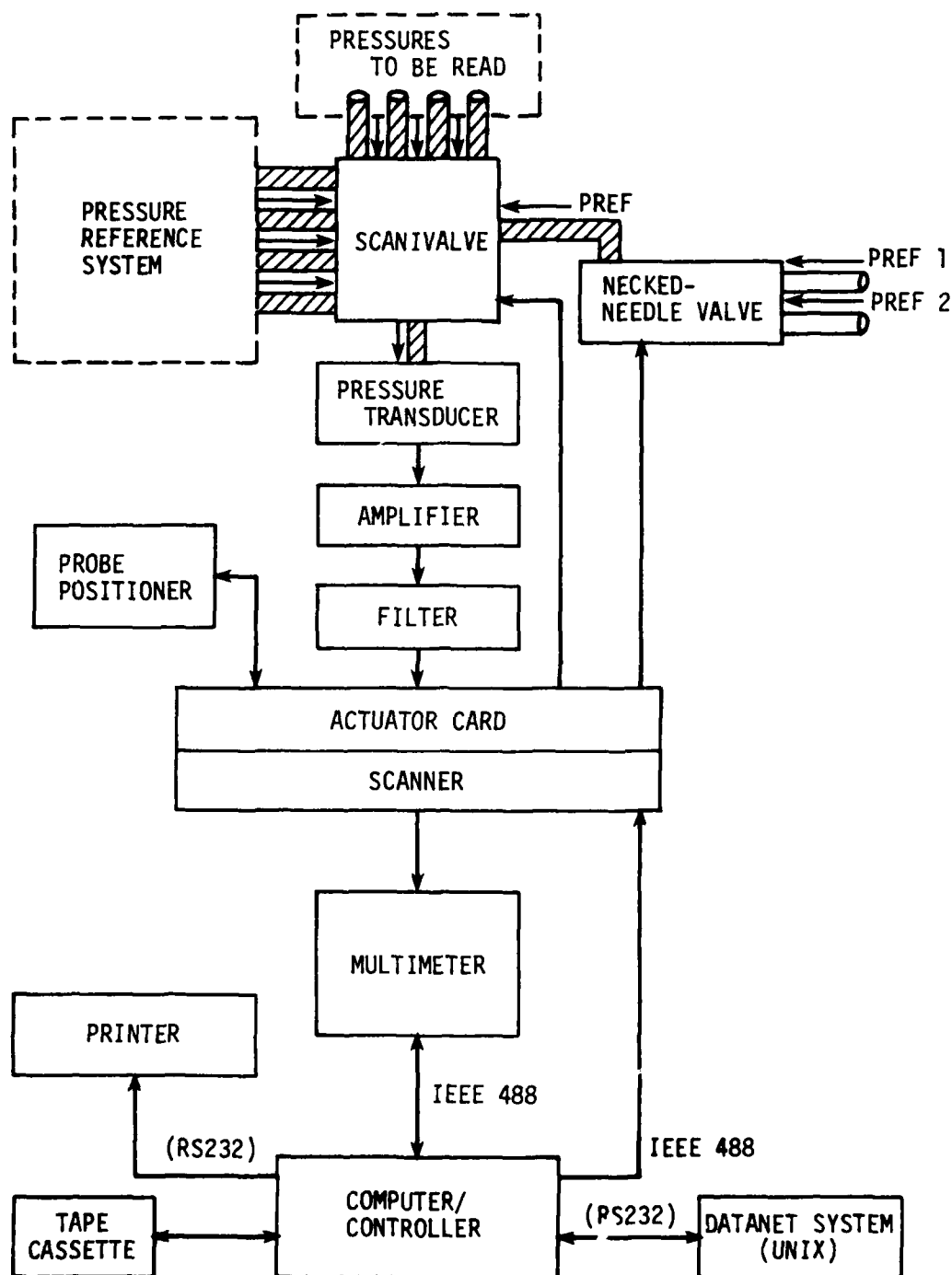
Figure 2. Component Diagram of Data Acquisition and Experiment Control System, Task I.

± 0.7 m of water is used. The probe actuator being used is an LC Smith Model BBR-18-180, ⌣ ⌣ the probe indicator is MODEL DI-3R.

A water column and balance pressure reference system has been constructed to provide on-line calibration of the pressure transducer [Ref. 2]. Using this system, four reference pressures are supplied with a precision of better than 0.07 mm of water. The calibration pressures, along with the other recorded pressures and zeros, are shown in the tabulation of Scanivalve port assignments in Table 1. As seen in Table 1, two different reference pressures are used (the plenum total pressure and the pressure from column C) in the pressure reference system. This switch of reference pressure on the Scanivalve is accomplished by a solenoid-driven necked-needle fluid switch (Scanivalve NN0602/1P-2T).

The PET computer or controller of the self-supporting data acquisition and experiment control system just described may also, through use of a second RS232 serial adaptor, be operated as a remote terminal in the University Computational Center DATANET system. This latter system, incorporating a PDP 11/34 computer and high-capacity disk units, is a university-wide high-speed recirculating digital network of mini- and microcomputers in experiment control and data acquisition. A file management system (UNIX) is used for collection of experimental data and program files, and assembled object code can be directly down-loaded into the remote terminals for subsequent execution. Also, a data link is to be made in the near future between DATANET and the University mainframe computer to provide further expanded data reduction and computing capability.

9

Table 1. Scanivalve Pressure Port Assignments for Experimental Passage
Rig, Task I.

Port	Pressure Measurement	Reference Pressure	Comment
1	Water column A	Water column C	Calibration
2	Water column C	Water column C	Zero
3	Water column B	Water column C	Calibration
4	Water column C	Water column C	Zero
5	Atmosphere	Water column C	Calibration
6	Water column C	Water column C	Zero
7	Water column D	Water column C	Calibration
8	Water column C	Water column C	Zero
9	P_o	Water column C	Plenum pressure
10	Water column C	Water column C	Zero
11	P_4	P_o	Probe
12	P_o	P_o	Zero
13	P_5	P_o	Probe
14	P_o	P_o	Zero
15-48	--	--	Open

Results to date of calibration runs on five-hole probes are shown
in Figure 3. This calibration was obtained using the plenum nozzle in
the low-speed flow loop as the flow source. In the calibration curves
shown, probe pressures P_1, and P_4 and P_5 are the total pressure and
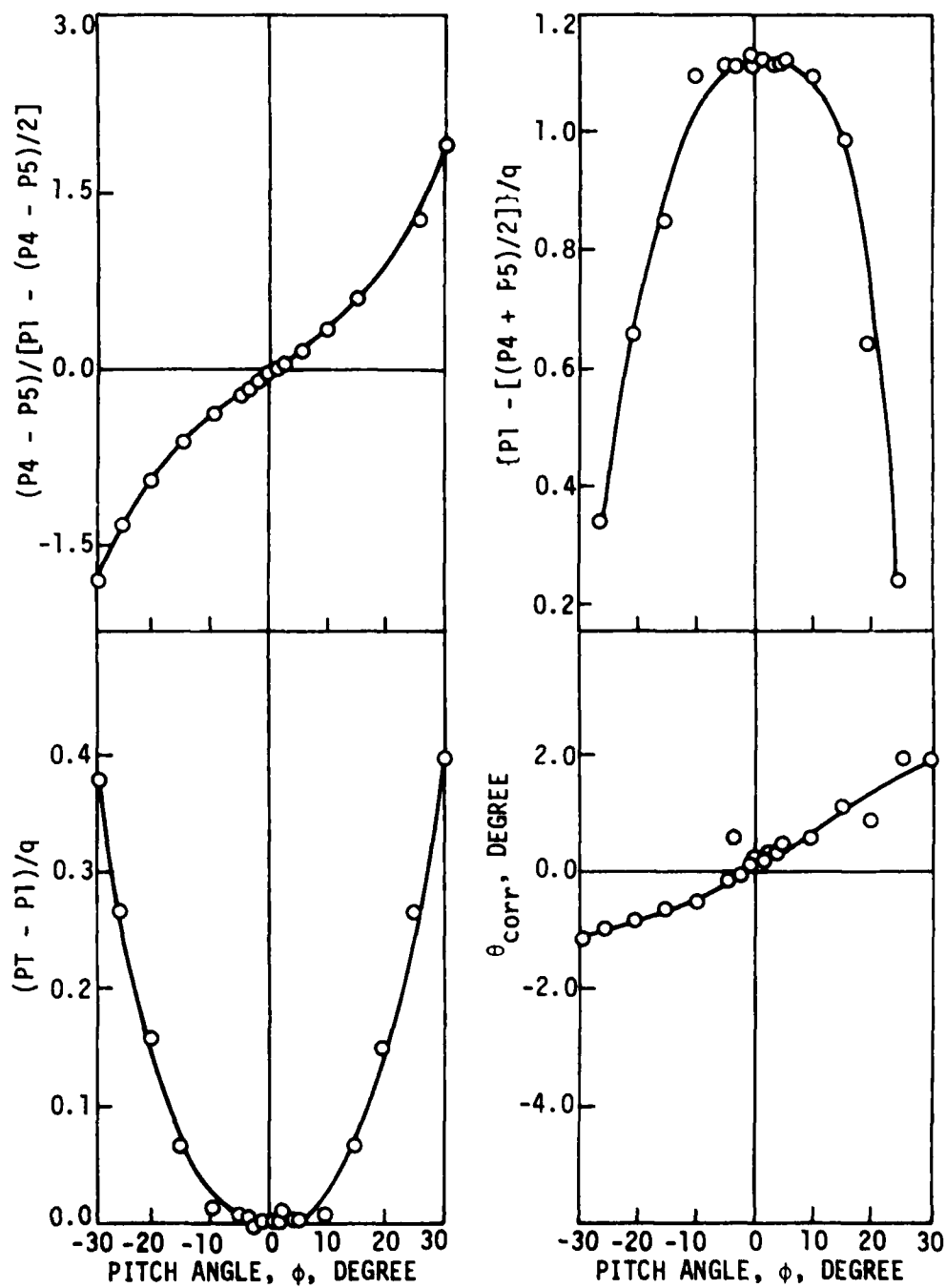pitch pressure measurements, respectively; P_T is the total pressure in

Figure 3. Calibration Curves for 5-hole Directional Pressure Probe.

11

the flow. The parameter θ_{corr} is the corrected yaw reading on the probe as a function of pitch angle of the probe in the flow. The testing was carried out over a velocity range of approximately 30 to 40 m/s with no discernible effect of velocity on the calibration.

The method of analysis to be used in Task I to calculate comparison solutions to the experimental passage measurements is the Stuart and Hetherington method [Ref. 3]. The program coding for this analysis has been completed, and a contour plotting package has been added for outputting of results. The computation of check cases and the comparison of analytical and experimental results will be a final subtask to be carried out in 1980.

2. TASK II: EVALUATION AND MANAGEMENT OF UNSTEADY FLOW EFFECTS IN AXIAL-FLOW COMPRESSORS

Data acquired under AFOSR Grant 76-2916 were used during the past year to complete an unsteady flow film. The periodic variation with rotor motion of representative velocity vector sheets at several radii behind the rotor and behind the stator of the first stage of the Iowa State University research compressor was illustrated. A time-sequence series of computer generated drawings based on experimental data were used. This film is a useful supplement to a film produced previously with AFOSR Grant 76-2916. The earlier film illustrated the extent of periodic flow unsteadiness and the formation, transport, and interaction of chopped blade wakes at selected positions of the first stage of the research compressor. It is apparent that variations in rotor relative exit flow are most appreciable in the middle portion (30 to 70 percent passage height from the hub), while periodic variations in stator exit

12

flow were most noticeable near the inner surface of the flow cross section.

In order to better understand the unsteadiness observed and to make the data useful to turbomachine designers, a detailed review of the literature related to blade-produced periodically unsteady flows in turbomachines was started in the Fall of 1978 and continues. The conclusions reached by Spring of 1979 are documented in Reference 4. Additional literature is currently being acquired and studied to update this aspect of the task.

In order to ascertain whether varying the relative circumferential positions of the inlet guide vane (IGV) and stator rows of the research compressor would result in measurable performance (deviation angle and total-pressure loss) changes, the compressor was operated at 2400 rpm and detailed time-average total-pressure measurements were acquired for different circumferential positions of the IGV and first stator rows. At a lower rotor speed (1400 rpm), similar tests indicated an appreciable difference in inlet noise for different relative circumferential positions of the IGV and stator rows. However, data obtained on total-pressure loss and deviation angle were inconclusive.

At the higher rotor speed, minimum and maximum noise circumferential positions of the first stator relative to the IGV row were identified. The difference in noise-sound pressure level was about 10 dB in the octave band including the blade passing frequency. Numerous total-pressure and yaw angle data were obtained behind the first stator for these two reference positions of the first stator. Some total-pressure

13

and yaw angle data were also obtained for the flow entering the first
stator row. Contour graphs of the time-average total-pressure measure-
ments behind the first stator are displayed in Figure 4. Pitch- and
time-average values of total pressure at various radii are compared in
Figure 5. Representative time-average yaw angle data are shown in
Figure 6. Although the annulus cross-section distribution of stator
exit time-average total pressure varies appreciably with change of
relative circumferential positioning between the IGV and stator rows,
the pitch- and time-average total pressures do not. Also, the stator
exit free-stream angles do not seem to depend significantly on circum-
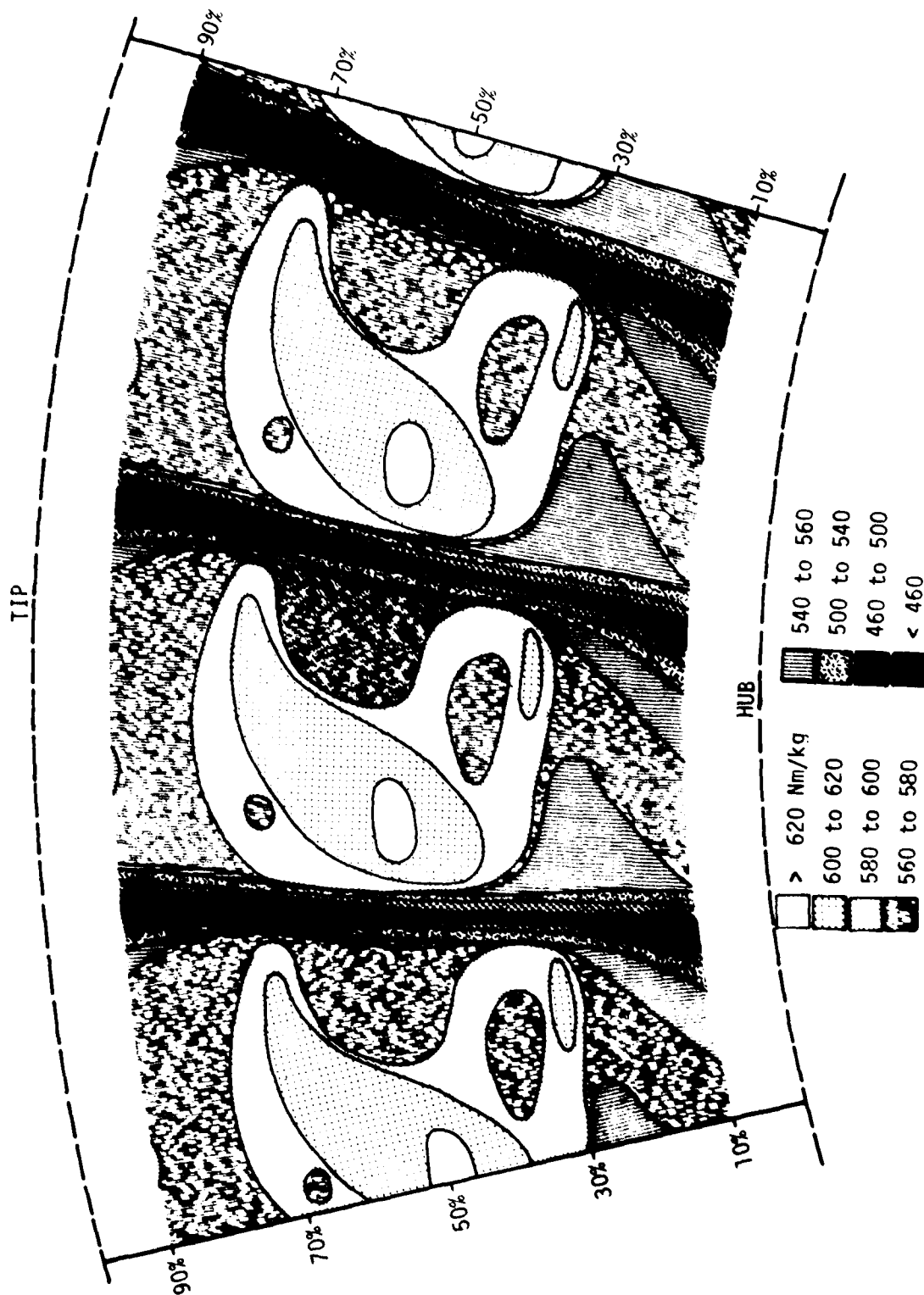ferential positioning of the first stator row.

Periodic-average total-pressure data for the first stage will be
acquired in the near future with a fast-response total-pressure probe.
The unsteady variation of rotor and stator exit-flow total pressure
with rotor motion will be studied. This kind of data should indicate
some important details about the unsteady energy transfer that occurs
in turbomachines.

3. TASK III: DEVELOPMENT OF A DESIGN-SYSTEM ORIENTED DEVIATION
   ANGLE PREDICTION EQUATION FOR ADVANCED COMPRESSOR AND FAN
   CONFIGURATIONS

Recent analytical (USAF/AFAPL Contract F33615-76-C-2090) [Ref. 5]
and computational (NASA Grant NsG-3033) [Ref. 6] work has suggested a
correlation of compressor and fan cascade-flow turning angles with
blade-profile boundary layer development characteristics. The results
of these investigations were integrated and extended (USAF/AFOSR Grant
78-3609) to cover more challenging test cases involving more of the
variables existing in real compressor flows.
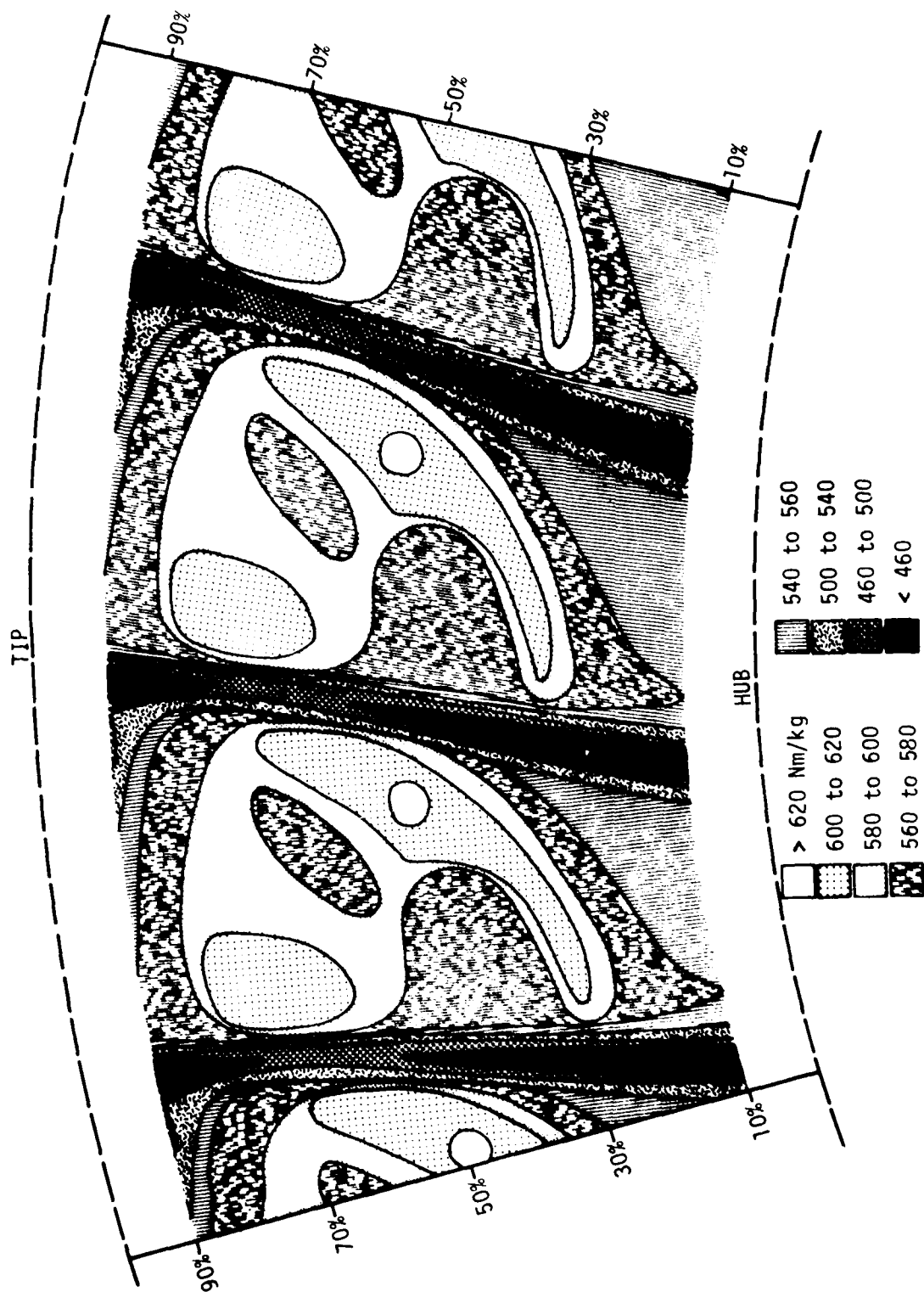
(a) MINIMUM NOISE CIRCUMFERENTIAL POSITIONING, $YO_{IGV}/S_S = 0$, $YO_{1S}/S_S = 0.159$

Figure 4. Time-Average First Stator Exit Flow Total-Pressure Variation with Stator/IGV Circumferential Positioning (2400 rpm).

15

(b) MAXIMUM NOISE CIRCUMFERENTIAL POSITIONING, $YO_{IGV}/S_S = 0$, $YO_{1S}/S_S = 0.719$

Figure 4. (Concluded).

16

CIRCUMFERENTIAL- AND TIME-AVERAGE TOTAL PRESSURE, N.m/kg

640
630
620
610
600
590
580
570
560
550
540
530
520
510
500

△ FIRST ROTOR EXIT
□ FIRST STATOR EXIT, $YO_{IGV}/S_S = 0$; $YO_{1S}/S_S = 0.159$
o FIRST STATOR EXIT, $YO_{IGV}/S_S = 0$; $YO_{1S}/S_S = 0.719$

0   10   20   30   40   50   60   70   80   90
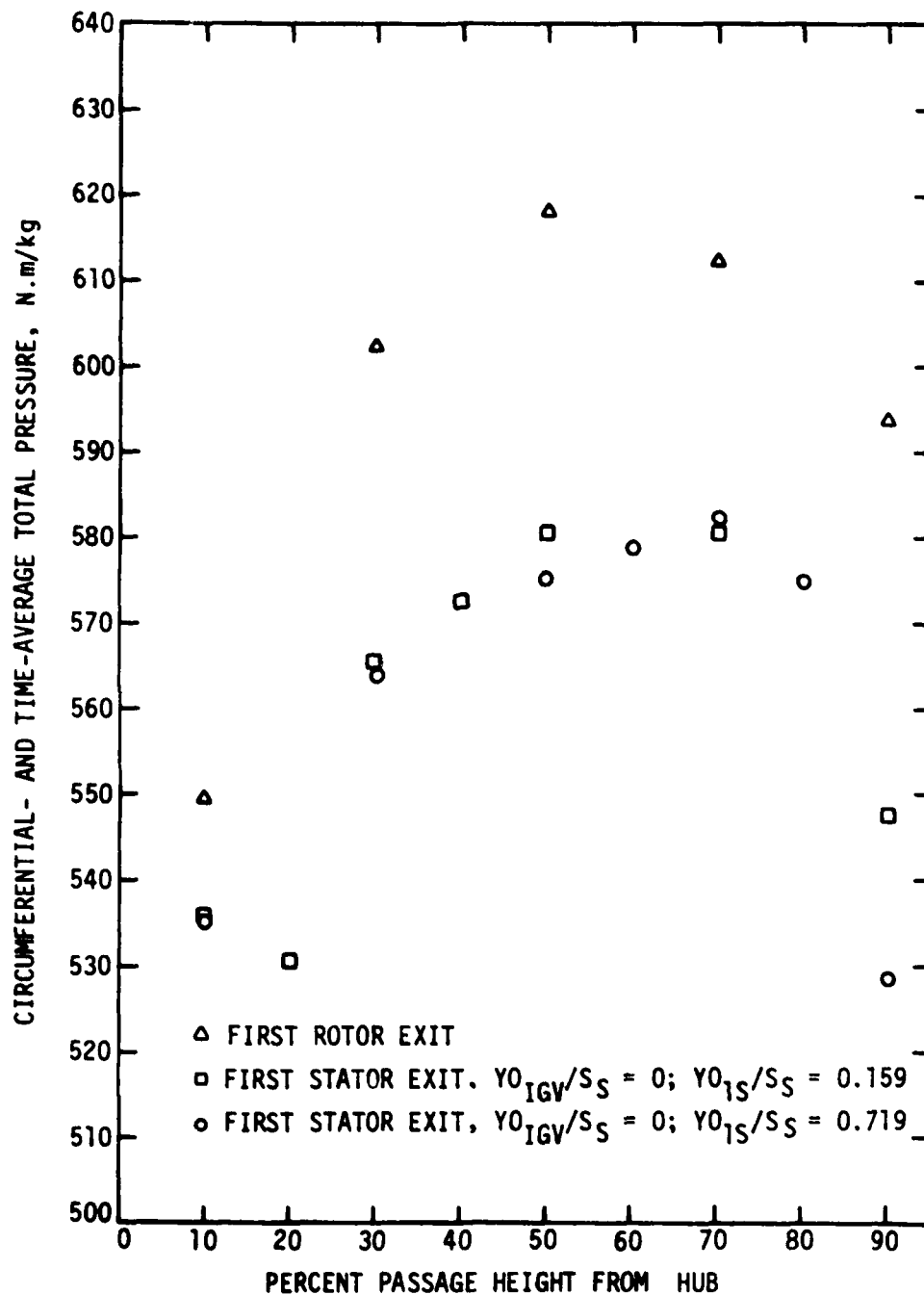
PERCENT PASSAGE HEIGHT FROM HUB

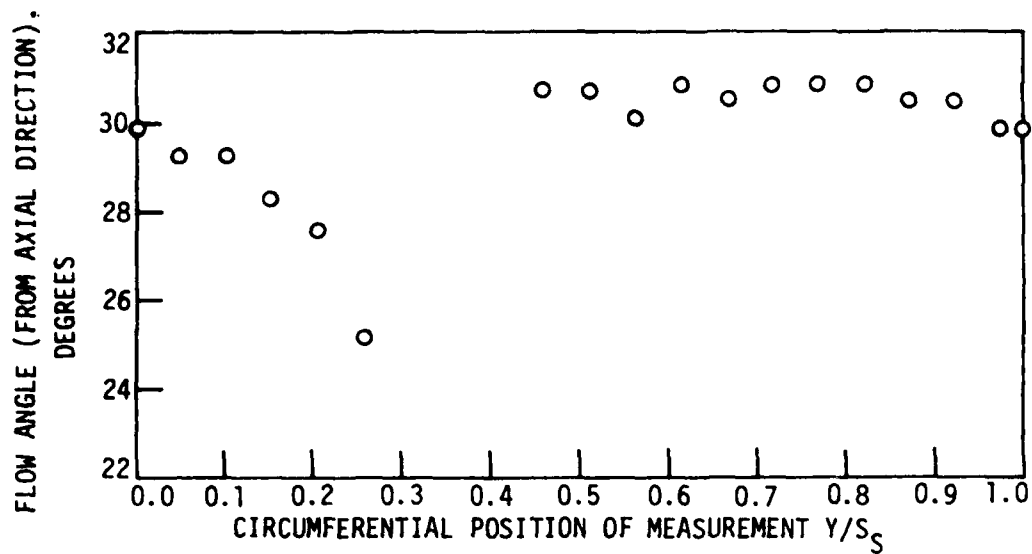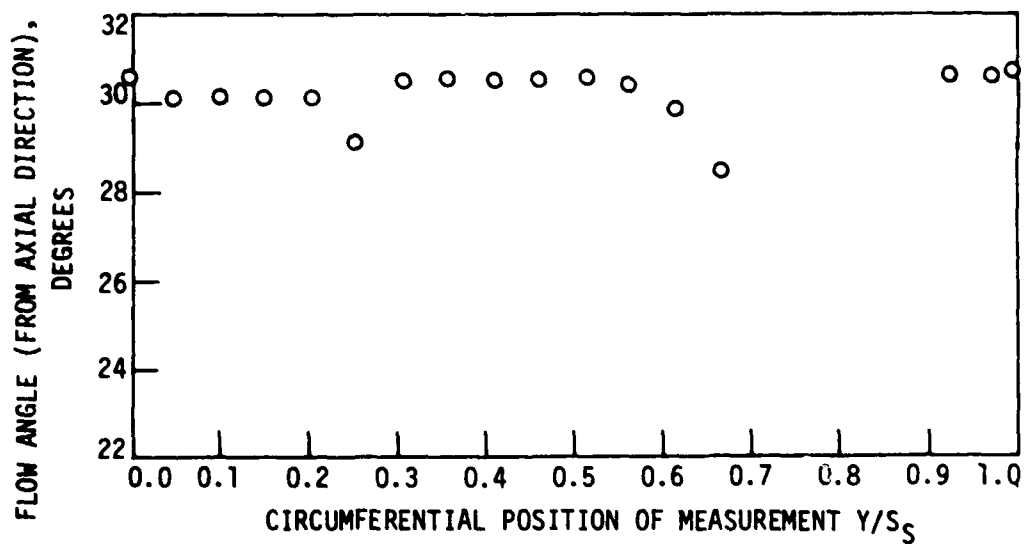Figure 5. Pitch- and Time-Average First Stator Exit Flow Total-Pressure
Variation with Stator/IGV Circumferential Positioning (2400 rpm).

17

(a) $YO_{IGV}/S_S = 0$; $YO_{1S}/S_S = 0.159$

(b) $YO_{IGV}/S_S = 0$; $YO_{1S}/S_S = 0.719$

Figure 6. Time-Average First Stator Exit Flow Angle Variation with Stator/
IGV Circumferential Positioning at 50 Percent Passage Height from
the Hub (2400 rpm).

Task III, which is directed toward the development of a design-system quality deviation angle prediction equation for advanced compressor and fan cascade configurations, has carried on this work. It was found in Reference 5 that there were few cascade data sets available with adequate information to give insight into the nature of the interaction of the boundary layer characteristics and the blade cascade deviation angle. Therefore, the computation method of Reference 6 was used in the current investigation to calculate the inviscid-viscous flow in the blade-to-blade passage and to obtain the boundary layer development characteristics and the outlet fluid flow angles for typical cascade geometries. Test configurations which involved many of the variables existing in real compressor flows were chosen. Each test case included some experimental data which was used to verify the validity of the computational model.

Several changes were made in the original computer program to better model the additional test configurations. A new differentiation scheme was used to determine the surface pressures near the trailing edge of the blade. This differentiation method provided smoother and more consistent surface pressure distributions than did the previous spline fitting method. The better estimation of surface pressures also improved calculation convergence.

The program was also modified to model small regions of supersonic flow. The modification was that suggested and outlined by Jerry Wood of the NASA-Lewis Research Center. The modification has proven to be useful, though when compared to experimental data, it underestimates the peak

Mach number. The total-pressure loss model was also modified to account for changes in the thickness and the radial location of the streamsheet downstream of the trailing edge.

Eight test configurations which involved a wide range of variables in real compressor flows were selected. The variables included incidence angle, inlet Mach number (high speed, transonic), inlet Reynolds number (low Reynolds number, laminar separation), and axial-velocity density ratio (AVDR). Table 2 shows the test configurations and the significant variables for which computations were made.

The double circular arc cascade [Ref. 7] provided insight into the effect of the AVDR on the flow field. Figures 7 and 8 show the large discrepancy which can exist between the surface pressures if the distribution of AVDR is not correctly modelled. Additional insight into the effect and distribution of AVDR was gained in communications with H. Starken [Ref. 7].

Variation of incidence for the 10A30/27.6π45 cascade [Ref. 8] produced computed fluid turning which was similar to that experimentally measured. The experimental measurements also included the distribution of velocity throughout the flow field. At an inlet Mach number of 0.79, the computed maximum flow field velocities are lower, but still favorable, when compared with the experimental measurements.

The computed flow through the 65-(12)10 cascade [Ref. 9] at low Reynolds number displayed the effect of the boundary layer on direction of fluid flow (Figure 9). The high-speed computation does not compare favorably with the measurements, possibly because axial-velocity density ratios other than 1.0 occurred in the experimental data.

Table 2. Test Configurations and Significant Variables Tested.

Blade Section	Reference	γ (deg.)	σ	M_1	Re_c	Experimental Data Available					Significant Variables Tested
						Flow Field Measurements	Surface Pressures	Fluid Turning Angle	Total-Pressure Loss	Boundary Layer Characteristics	
Double Circular ARC φ = 48	7	15	1.629	0.6⁻	1.26×10^6		•	•	•		Axial-velocity density ratio
10A30/27.6π45	8	27.4	1.3	0.4-0.83	$3.7-7.0 \times 10^5$	•	•	•	•		Incidence Mach number
65-(12)10	9	45.7	1.0	0.13-0.06 0.5-0.9	$3.2-1.5 \times 10^5$ $1.3-2.3 \times 10^6$		•	•	•		Reynolds number Mach number
65-($12A_2I_{8b}$)10	9	45.3	1.0	0.5-0.84	$1.3-2.2 \times 10^6$		•	•	•		Mach number
115 Stator	10	16.5	3.39	0.7	1.4×10^6			•	•	•	Incidence
Prescribed Velocity Distribution	11	35.5	1.2	0.05	1.5×10^5		•	•	•		Incidence Axial-velocity density ratio
L03C-4	12	48.5	1.61	0.7-0.9	$7.6-10 \times 10^5$	•		•			Mach number Axial-velocity density ratio
65-(18)15 Radial Cascade	13	27.0	1.24	0.43	1.7×10^5				•		Axial-velocity density ratio

21

Figure 7. Calculated Surface Pressures Compared with Experimental
Data for the DCA ϕ = 48° Blade Cascade.
M_1 = 0.64 Re_c = 1.26 × 10^6 β_1 = 40°   i = 1°
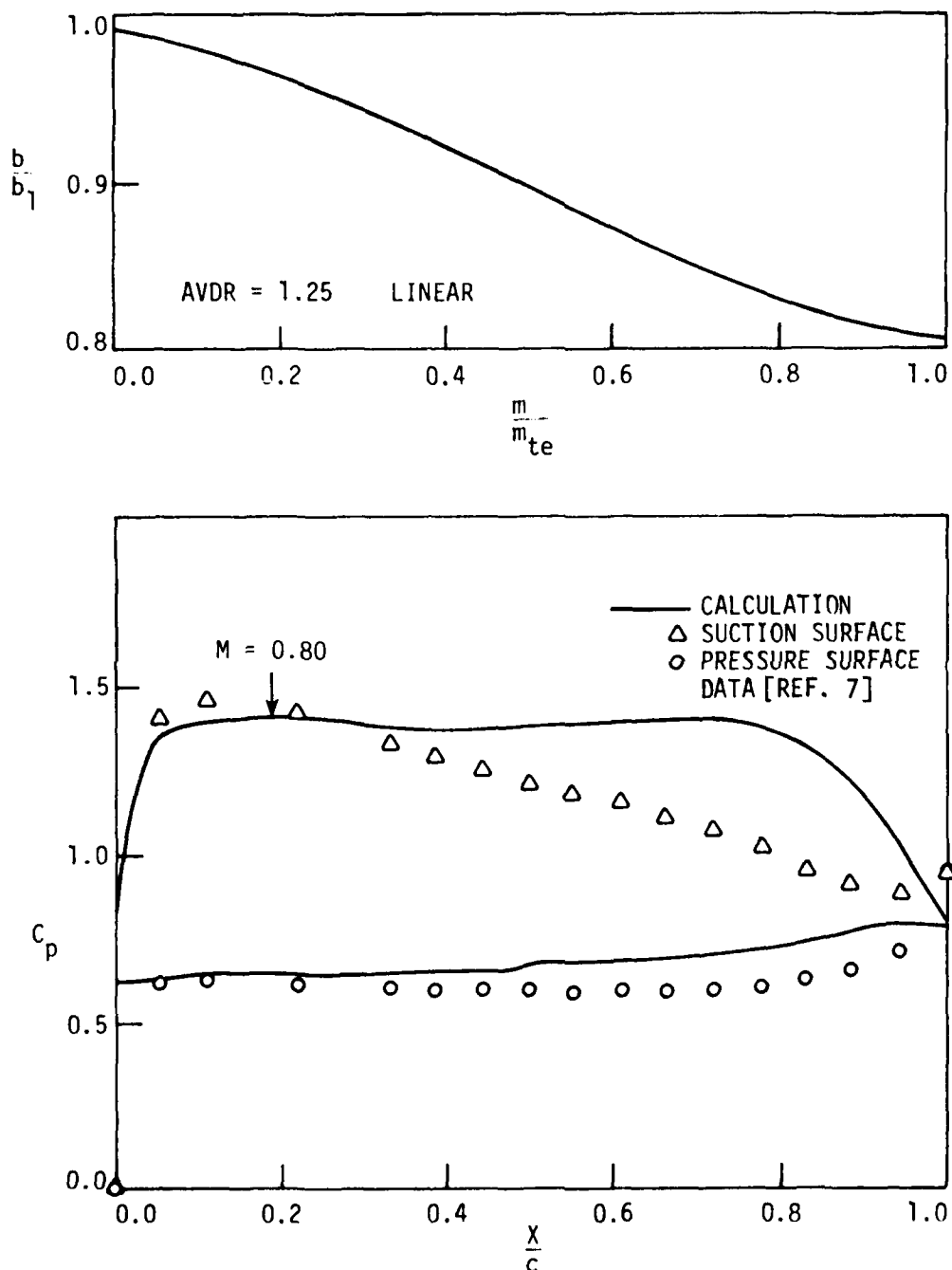D = 0.244 γ = 15° σ = 1.629   c = 90 mm
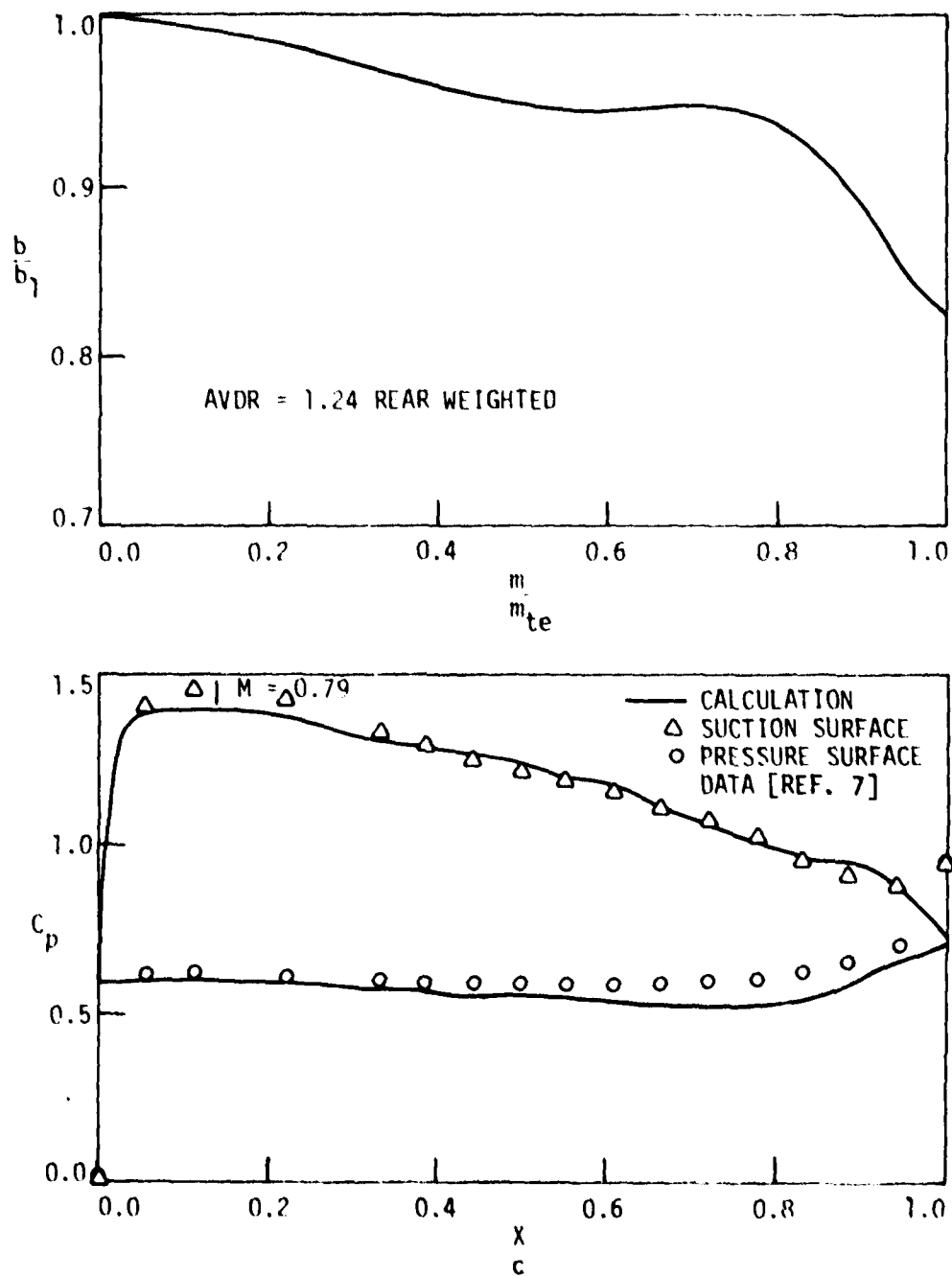
Figure 8. Calculated Surface Pressures Compared with Experimental
Data for the DCA ϕ = 48° Blade Cascade.
M_1 = 0.64 Re_c = 1.26 × 10⁶ β_1 = 40° i = 1°
D = 0.244 γ = 15° σ = 1.629 c = 1.24
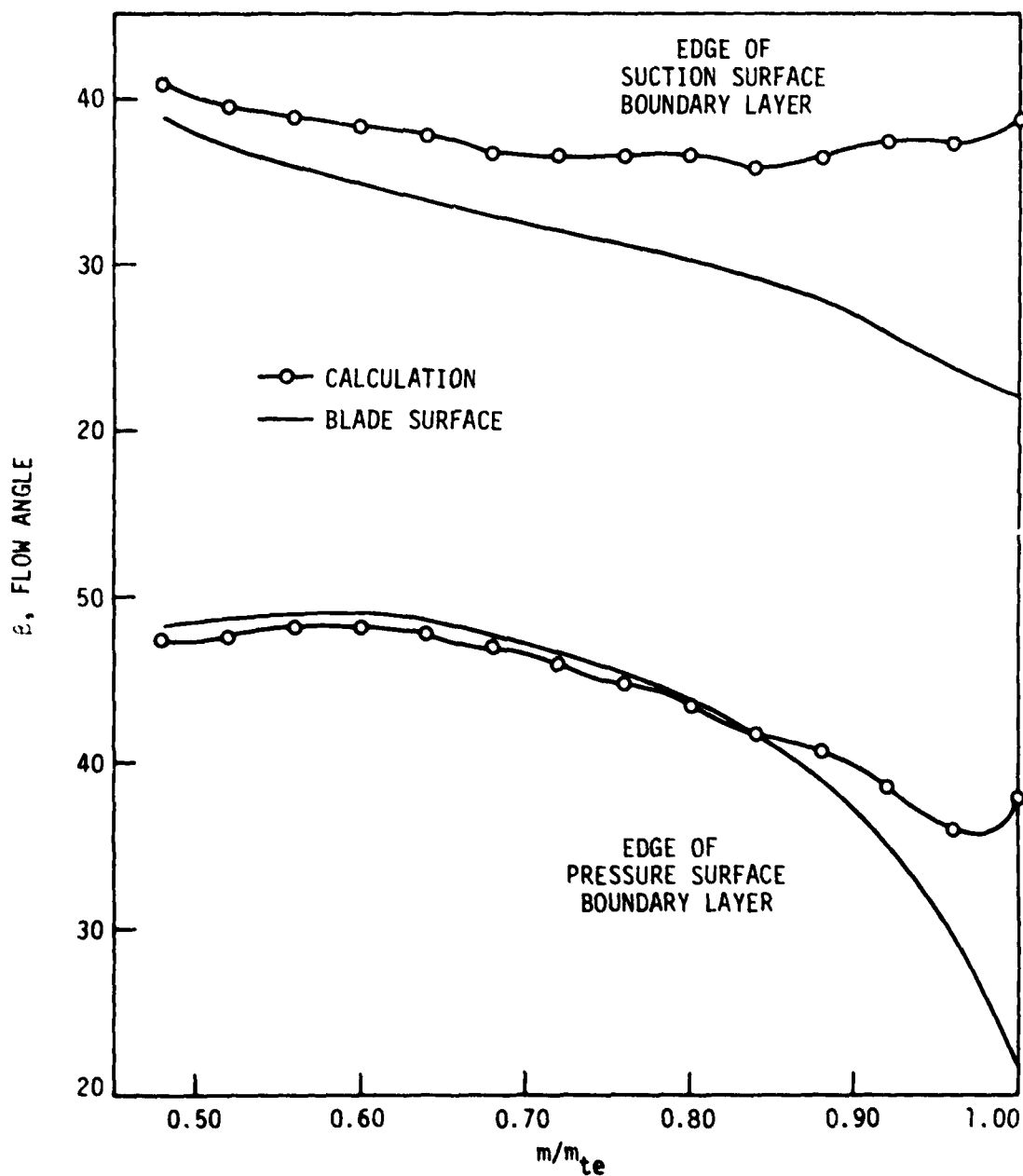
Figure 9. Calculated Flow Angle at the Edge of the Suction and Pressure Surface Boundary Layers for the NACA 65-(12)10 Blade Cascade. $M_1 = 0.06$, $Re_c = 1.47 \times 10^5$, $\beta_1 = 57.7^\circ$, $\alpha = 12^\circ$, $D = 0.42$, $\gamma = 45.7^\circ$, $\sigma = 1.0$, $c = 124$ mm, AVDR = 1.0

24

Figure 10. Calculated Suction Surface Boundary Layers Compared with Experimental Data for the 115 Stator Blade Cascade.
$M_1 = 0.7$ $Re_c = 1.4 \times 10^6$ $\beta_1 = 51°$
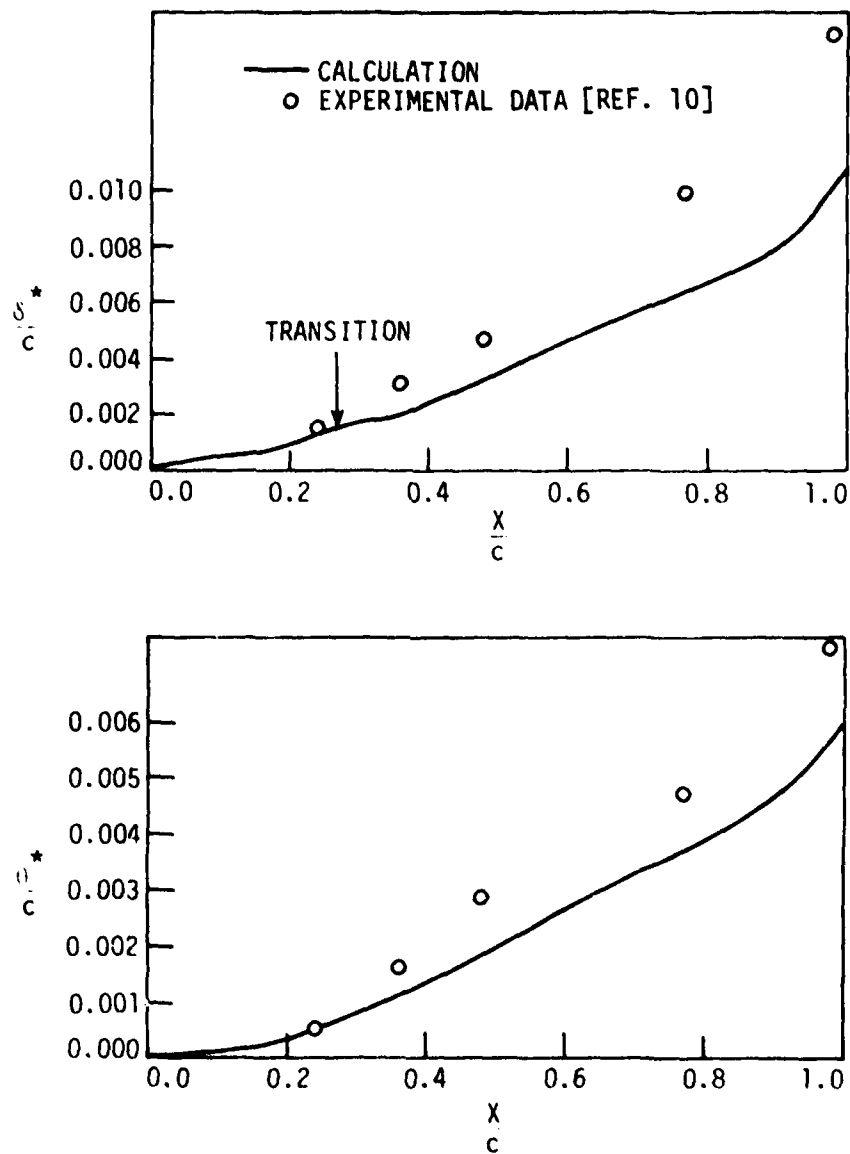$D = 0.577$ $\gamma = 16.5°$ $\sigma = 3.39$ $c = 95.6$ mm

The computed high-speed flow through the $65-(12A_2I_{8b})10$ cascade
[Ref. 9] compared well with experimental measurements. At higher Mach
numbers, there was again an underestimation of the peak Mach number.

The ONERA 115 Stator cascade [Ref. 10] was the only configuration
for which blade-surface boundary layer measurements were available. The
comparison of the calculated boundary displacement and momentum thickness
distribution with the experimental measurements was very good (Figure 10).

The Prescribed Velocity Distribution cascade [Ref. 11] provided a
series of test cases at low Reynolds number for which the AVDR was varied
at several incidence angles. This also showed the change in the boundary
layer characteristics with the variation of incidence and axial-velocity
density ratio.

Experimental measurements for the L03C-4 test configuration [Ref. 12]
were taken at high speed for various inlet angle and AVDR combinations.
Laser two-focus velocimeter measurements of the flow field are available
and will be used for comparison.

A NACA 65-(18)15 cascade [Ref. 13] was experimentally tested both
as a radial and an axial cascade. Computations were made for both
radial and axial cascade arrangements to show the effect of the AVDR on
the cascade.

4. TASK IV: EXPERIMENTAL STUDY OF MERITS OF SPECIFIC FLOW PATH
   GEOMETRY CHANGES IN CONTROLLING SECONDARY FLOWS IN AXIAL-FLOW
   COMPRESSORS

The suitability of using the existing Iowa State research compressor
blading (used, for example, in Task II) for a baseline configuration for
performance comparison was examined. It was decided that a new set of

blades should be designed and built. Higher blade-chord Reynolds number, more suitable blade material, conventional blade section shapes, a favorable ratio of number of rotor blades to number of stator blades, and elimination of inlet guide vanes are some of the improvements expected.

The new baseline blades were designed with the aid of computer codes described in References 14 and 15. The preliminary design code [Ref. 14] is based on simple radial equilibrium of the duct flow between blade rows. A constant spanwise distribution of blade-element efficiency was involved for each blade row. For the preliminary design phase, a free-vortex swirl velocity distribution behind the rotor was used. Values of input parameters, including rotor tip and stator hub diffusion factors, rotor and stator tip axial-velocity ratios, blockage factors and rotor and stage polytropic efficiencies, were varied until reasonable input and output were achieved. The final design code [Ref. 15] is based on a streamline curvature type solution of the two-dimensional axisymmetric approximation of actual axial-flow compressor flow. It involves duct-flow stations outside blade rows. Velocity diagrams, however, are determined at blade leading and trailing edges. The code produces detailed aerodynamic, as well as blade geometry data.

The new baseline configuration will consist of two identical stages as illustrated in the meridional plane sketch of Figure 11. The flow path involved, as well as the rotor drive system and flow rate control, will be the same as that used in Task II. A summary of pertinent design data is given in Table 3. Representative blade section profiles are shown in Figures 12 and 13. Blade-element losses were approximated with

27

BASELINE STATOR
LEADING EDGE
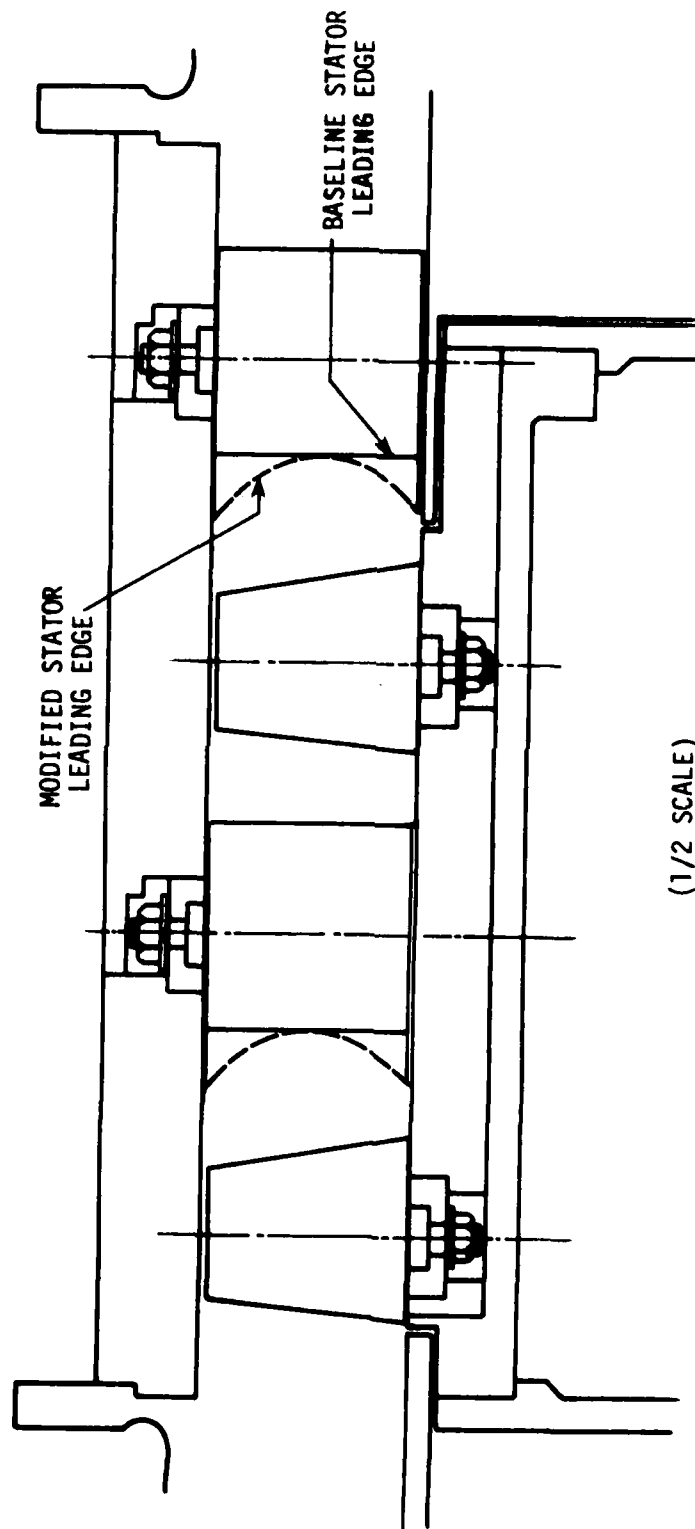
MODIFIED STATOR
LEADING EDGE

(1/2 SCALE)

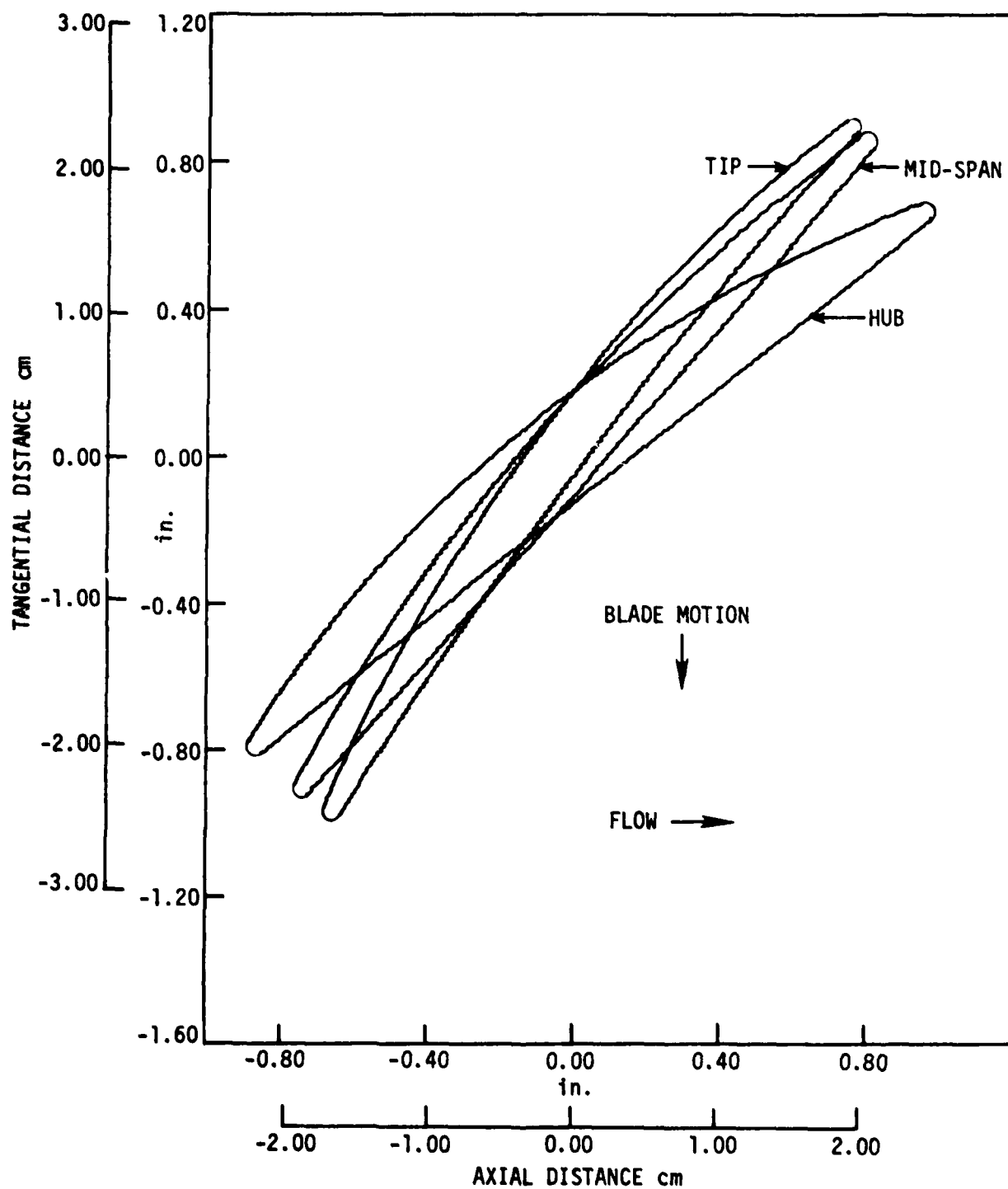Figure 11. Meridional Plane View of New Blading.

28

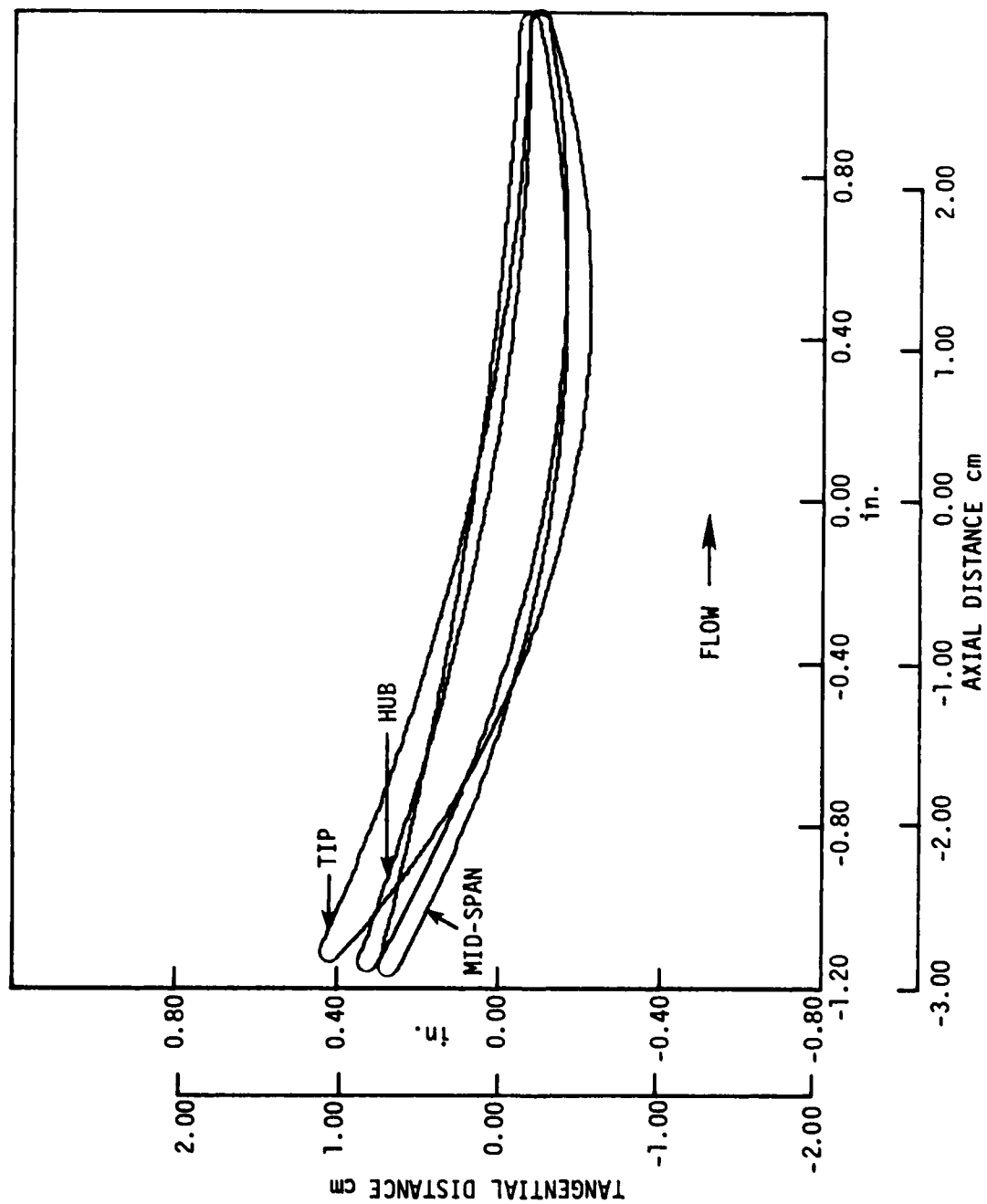Figure 12. Representative Baseline Configuration Rotor Blade Sections.

Figure 13. Representative Baseline Configuration Stator Blade Sections.

30

values from Figure 203 of Reference 16. Blade-element incidence and deviation angles were estimated using the method proposed in Chapter VI of Reference 16. Approximate blockage factors used during the preliminary design phase were specified. Constant energy addition over the rotor span was selected.

Table 3. Summary of Baseline Compressor Design Data.

Rotor speed	2400 rpm
Flow rate	5.25 lb_m/s (2.38 kg/s)
Pressure ratio	1.019
Number of blades	
Rotor	21
Stator	30
Blade material	aluminum
Blade chord	2.39 in. (6.07 cm)
Blade profile	double circular arc
Flow path	
Hub radius	5.60 in. (14.22 cm)
Tip radius	8.00 in. (20.32 cm)

A modified stator blade with forward symmetrical sweep of the blade leading edge in the endwall regions is being designed. Air Force Aero Propulsion Laboratory experience suggests that such a modification may lead to improved stator performance. The previously mentioned computer code [Ref. 15] has already been used to aerodynamically design a version

of this blade for use with the baseline rotor. Except for nonconstant chord distribution, the baseline design options were used. Some representative blade section profiles are shown in Figure 14. Because of the unusual nature of this blade, an independent analysis will be made using the AFAPL UD0300 axial-flow compressor design code [Refs. 17 and 18]. Like the program in Reference 15, UD0300 employs the streamline curvature method to determine the axisymmetric approximation of the actual compressor flow. Unlike the program in Reference 15, UD0300 allows placement of calculation stations within blade rows, a feature that may be very important in designing the modified stator. Results from both computer codes will be compared before the blading is fabricated.

Performance testing of the baseline compressor is scheduled to begin in 1980 and will consist mainly of time-average and periodic-average total-pressure and flow velocity measurements. Design-point operation flow field properties will be ascertained in detail. Some off-design data, such as the rotating stall limit, will be acquired.

Testing of the modified compressor is anticipated later in 1980. Time-average and periodic-average total-pressure and flow velocity measurements for design-point and off-design operation will be acquired and compared with baseline results.

5. TASK V: DEFINITION OF EXPERIMENTAL PROGRAMS AND FACILITIES APPROPRIATE FOR UNIVERSITY TURBOMACHINERY RESEARCH PROGRAMS

This study was scheduled for the second year of the contract and was initiated 1 October 1979.
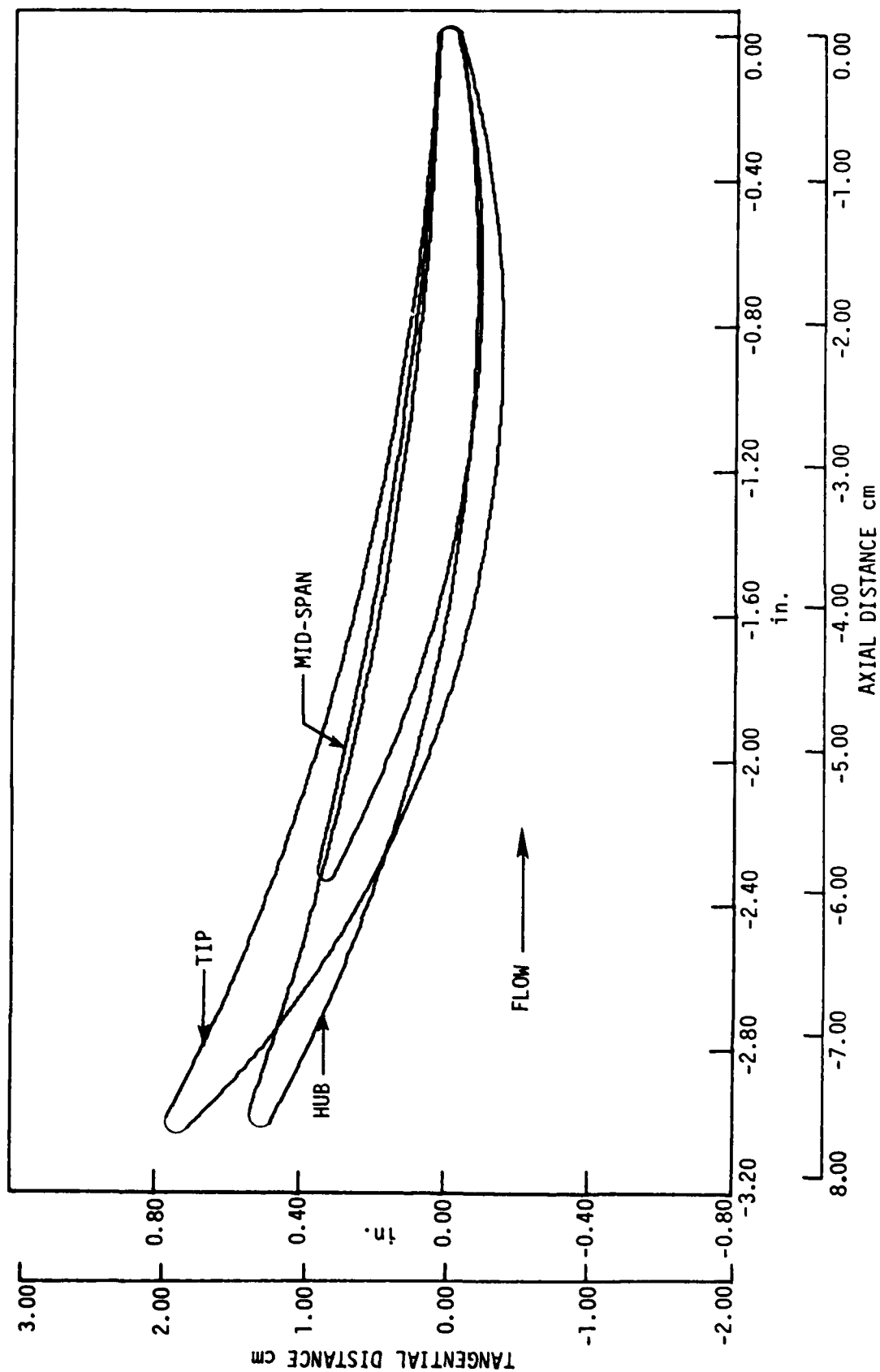
Figure 14. Representative Modified Stator Blade Sections.

SECTION III

PUBLICATIONS

The following list includes documents based entirely, or in part,
on research supported under the current contract.

1. Kavanagh, P. The Stuart and Hetherington Numerical Solution Method
    for Three-Dimensional Compressible Internal Flows. Engineering
    Research Institute Report. ISU-ERI-Ames-78310, TCRL-12. Iowa State
    University, Ames, Iowa. 1978.

2. Morgan, Betsy D. A Water Column Balance Pressure Reference System.
    Turbomachinery Components Research Program. Unpublished report.
    Department of Mechanical Engineering. Iowa State University, Ames,
    Iowa. 1979.

3. Wagner, J. H., Okiishi, T. H., and Holbrook, G. J. Periodically
    Unsteady Flow in an Imbedded Stage of a Multistage, Axial-Flow Turbo-
    machine. Trans. ASME. Journal of Engineering for Power. 101:42-51.
    1979.

4. Okiishi, T. H. Turbomachine Wake Transport and Interaction. In
    von Karman Institute for Fluid Dynamics Lecture Series Unsteady Flow
    in Turbomachines Notes. Rhode-St.-Genèse, Belgium. 1979.

5. Okiishi, T. H. Some Fundamental Unsteady Flow Measurements in Turbo-
    machines. In University of Tennessee Space Institute Lecture Series
    Flow Induced Vibration Problems and Their Solutions in Practical
    Applications: Turbomachinery, Heat Exchangers and Nuclear Reactors
    Notes. Tullahoma, Tennessee. 1979.

6. Okiishi, T. H., and Schmidt, D. P. *Measurement of the Periodic Variation of Turbomachine Flow Fields.* In <u>Proceedings of the Dynamic Flow Conference 1978 on Dynamic Measurements in Unsteady Flows</u>. Proceedings of the Dynamic Flow Conference 1978. Skovlunde, Denmark. 1979.

7. Hansen, E. C., Serovy, G. K., and Sockol, P. M. Axial-Flow Compressor Turning Angle and Loss by Inviscid-Viscous Interaction Blade-to-Blade Computation. ASME Paper 79-GT-5. 1979 (to be published in Trans. ASME. <u>Journal of Engineering for Power</u>).

8. Hansen, E. C., Serovy, G. K., and Sockol, P. M. Axial-Flow Compressor Turning Angle and Loss by Inviscid-Viscous Interaction Blade-to-Blade Computation. NASA Technical Note, in review process.

9. Serovy, G. K., and Hansen, E. C. Computation of Flow in Radial- and Mixed-Flow Cascades by an Inviscid-Viscous Interaction Method. Paper in preparation for AGARD Specialists Meeting on Centrifugal Compressors, May 5-9, 1980. Brussels, Belgium.

SECTION IV

PROGRAM PERSONNEL

Three principal investigators share responsibility for the current program.

- George K. Serovy, Anson Marston Distinguished Professor in

    Engineering, Tasks III, IV, V

- Patrick Kavanagh, Professor of Mechanical Engineering, Task I

- Theodore H. Okiishi, Professor of Mechanical Engineering,

    Tasks II, IV

Three graduate-level engineers have also been associated with the work.

- Elmer C. Hansen, Post-Doctoral Research Fellow (to 1 October

    1979), Tasks III, IV

- William C. Zierke, Graduate Research Assistant, Task II

- Michael D. Hathaway, Graduate Research Assistant, Task IV

During the initial phases of the research, several undergraduate students in Mechanical Engineering have made useful contributions. This has been an effective mechanism for introducing undergraduates to the research activity in turbomachinery.

- Betsy D. Morgan, Undergraduate Assistant (to 1 June 1979), Task I

- J. Scott Meline, Undergraduate Assistant (to 1 June 1979), Task I

- Brian H. Pigg, Undergraduate Assistant (to 1 June 1979), Task 1

- Douglas A. Hottman, Undergraduate Assistant, Task I

- Allen D. Dvorak, Undergraduate Assistant, Task I

- Paul G. Smith, Undergraduate Assistant, Task I

- Russell L. Allen, Undergraduate Assistant, Task III

SECTION V

INTERACTION WITH FEDERAL AGENCIES AND INDUSTRY

The turbomachinery research program at Iowa State University has focused on projects which make a contribution to the development of design systems for advanced compressors, fans, and turbines for air-breathing aircraft propulsion systems. The current contract has not changed this focus and has involved numerous direct contacts with outside organizations.

Task II is a continuation of turbomachine unsteady flow measurement work initiated under AFOSR Grant 76-2916. Related interactions involving formal written discussions and informal conversations about measurement techniques and data are summarized below.

Organization and Nature of Contact	Individual Contacts
von Karman Institute for Fluid Dynamics, Rhode-St.-Genèse, Belgium; formal lectures, lab visit, other technical discussions	F.A.E. Breugelmans
Institut für Strahlantriebe und Turboarbeitsmaschinen, Technische Hochschule, Aachen, West Germany; lab visit and technical discussions, review of technical paper	H. E. Gallus
Turbopropulsion Laboratory, Department of Aeronautics, Naval Post-graduate School, Monterey, California; formal lecture, lab visit, and technical discussions	R. P. Shreeve

NASA-Lewis Research Center, Cleveland,   T. Strassazzar
Ohio; lab visit and technical discussions

The Trane Company, LaCrosse, Wisconsin;   D. P. Schmidt
telecom technical discussions

United Technologies Research Center,   J. H. Wagner
East Hartford, Connecticut; telecom
technical discussions

Department of Civil and Mechanical   G. J. Walker
Engineering, University of Tasmania,
Hobart, Tasmania; technical discussions

Department of Aerospace Engineering,   B. Lakshminarayana
Pennsylvania State University, University
Park, Pennsylvania; technical exchange of
data, formal discussion of research

University of Tennessee Space Institute,   M. Kurosaka
Tullahoma, Tennessee; formal lecture   J. E. Caruthers

Task III has involved use of experimental test cases selected to
demonstrate capabilities and limitations of the cascade flow field com-
putation system. It has also involved continued cooperation with the
initial sponsors at the NASA-Lewis Research Center. Mr. M. J. Hartmann,
Chief, Fluid System Component Division, Lewis Research Center, has
approved use of the NASA computation facilities for test case examples.

Organization and Nature of Contact	Individual Contacts
Air Research, Phoenix Division, Phoenix, Arizona; test cases	J. R. Switzer
Institut für Antriebstechnik, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt, Köln, West Germany; test cases, review of results	Dr. G. Winterfeld Dr. H. Starken Dr. J. Renken
Direction de l'Energetique, Office National d'Etudes et de Recherches Aérospatiales, Châtillon-sous-Bagneux, France; test cases, review of results	J. Fabri G. Meauzé
NASA-Lewis Research Center, Cleveland, Ohio; computation, test cases, review of results	M. J. Hartmann P. M. Sockol D. M. Sandercock J. F. Schmidt J. Wood

Task IV depends on substantial cooperation with USAF/AFAPL and industry. A list of the visits and telephone contacts for Task IV follows.

Organization and Nature of Contact	Individual Contacts
NASA-Lewis Research Center, Cleveland, Ohio; exchange of computer programs, review of designs	D. M. Sandercock J. E. Crouse

Air Force Aero Propulsion Laboratory, Wright-   Dr. A. J. Wennerstrom

Patterson Air Force Base, Ohio; discussion   Dr. C. Herbert Law

and review of designs for base and modified

stages

General Electric Company, Advanced Turbo-   Dr. D. C. Wisler

machinery Aerodynamics, Cincinnati, Ohio;   Dr. L. H. Smith, Jr.

review of design

Pratt & Whitney, East Hartford, Connecticut;   H. Weingold

discussion of blade fabrication problems   A. W. Stubner

SECTION VI

DISCOVERIES, INVENTIONS AND SCIENTIFIC APPLICATIONS

No fundamentally new concepts or devices have been developed.
However, Task IV will involve some blade design concepts which
originated in AFAPL and may, after experimental evaluation and develop-
ment, lead to improved multistage compressor performance.

SECTION VII

CONCLUDING REMARKS

The AFOSR-funded multi-task program has proceeded according to schedule, with only minor deviations caused by problems with equipment procurement and fabrication. These deviations were necessary to allow thorough design review and evaluation. The overall program has resulted in a high level of internal and external transfer of ideas and information, and is leading to the gradual buildup of a base of graduate and undergraduate student research personnel to complement the existing faculty research group. It is hoped that AFOSR and other government agencies, as well as industry, understand the importance of generating a regular flow of talented, young research specialists in the field of turbomachinery aerodynamics.

SYMBOLS AND NOTATION

AVDR	ratio of blade row exit to entrance axial velocity $\times$ density product
b	blade-to-blade streamsheet thickness
b_1	blade-to-blade streamsheet thickness at cascade entrance
C_p	pressure coefficient
c	blade chord length
D	diffusion parameter [Ref. 16]
i	incidence angle
M_1	cascade entrance Mach number
m	meridional distance measured from row leading edge
m_{te}	meridional distance to trailing edge
P_o	total pressure in plenum
P_1 or P1	
P_4 or P4	Pressures indicated by five-hole probe
P_5 or P5	
P_T or PT	local total pressure
q	dynamic pressure
Re_c	Reynolds number based on chord length
S_S	circumferential distance between two adjacent stator blades
X	distance along chord line
Y	circumferential distance from the reference meridional plane to the measurement point
YO_{IGV}	circumferential distance from the reference meridional plane to the reference IGV blade stacking axis
YO_{1S}	circumferential distance from the reference meridional plane to the reference first stator row blade stacking axis

47

α	angle of attack
β	local flow angle measured from axial direction
β_1	inlet flow angle measured from axial direction
γ	blade setting angle
δ^*	boundary layer displacement thickness
θ_{corr}	corrected flow yaw angle reading on the probe
θ^*	boundary layer momentum thickness
σ	solidity
ϕ	pitch angle or blade camber

REFERENCES

1. Eichhorn, R., and Fox, T. S. "A Method for the Construction of Flow Nozzles and Wind Tunnel Contraction Sections." Trans. ASME. _Journal of Fluids Engineering_. 99:772-773. 1977.

2. Morgan, Betsy D. A Water Column Balance Pressure Reference System. Turbomachinery Components Research Program. Unpublished Report. Department of Mechanical Engineering. Iowa State University, Ames, Iowa. 1979.

3. Kavanagh, P. The Stuart and Hetherington Numerical Solution Method for Three-Dimensional Compressible Internal Flows. Engineering Research Institute Report. ISU-ERI-Ames-78310, TCRL-12. Iowa State University, Ames, Iowa. 1978.

4. Okiishi, T. H. "Turbomachine Wake Transport and Interaction." In _von Karman Institute for Fluid Dynamics Lecture Series Unsteady Flow in Turbomachines Notes_. Rhode-St.-Genèse, Belgium. 1979.

5. Serovy, G. K. Deviation Angle/Turning Angle Prediction for Advanced Axial-Flow Compressor Blade Row Geometries. Final Report. USAF/AFAPL Contract F33615-76-C-2090. AFAPL-TR-77-81. 1978.

6. Hansen, E. C. Blade-Surface Boundary Layer and Wake Computational Models for Estimation of Axial Flow Compressor and Fan Blade-Row Deviation Angles and Losses. Unpublished Ph.D. Dissertation. Iowa State University, Ames, Iowa. 1978.

7. Starken, H., Breugelmans, F. A. E., and Schimming, P. Investigation of the Axial-Velocity Density Ratio in a High Turning Cascade. ASME Paper No. 75-GT-25. 1975.

8. Bunimovich, A. I., and Svyatogorov, A. A. "Aerodynamic Characteristics of Foil Compressor Cascades at High Subsonic Speeds." FTD-MT-24-69-68. April 26, 1968. Translation of "Lopatochnyye Mashiny i Struynyye Apparaty." Sbornik Statey. Vypusk 2. Moscow. Izdatel'stvo Mashinostroyenie. 1967. pp. 5-35.

9. Dunavant, J. C., Emery, J. C., Walch, H. C., and Westphal, W. R. High Speed Cascade Tests of the NACA 65-$(12A_{10})$10 and NACA 65-$(12A_2I_{8b})$10 Compressor Blade Sections. U.S. NACA RM L55I08. 1955.

10. Meauzé, G. Transonic Boundary Layer on Compressor Stator Blades as Calculated and Measured in Wind Tunnel. Paper given at International Symposium on Air Breathing Engines IV. 1979.

11. Masek, Z., and Norbury, J. F. "Low-Speed Performance of a Compressor Cascade Designed for Prescribed Velocity Distribution and Tested with Variable Axial Velocity Ratio. In Heat and Fluid Flow in Steam and Gas Turbine Plant. IME Conference Publication 3. 1973. pp. 276-287.

12. Weyer, H. B. Personal Communication. 1979.

13. Switzer, J. R. Personal Communication. 1979.

14. Bryans, A. C., and Miller, M. L. Computer Program for Design of Multistage Axial-Flow Compressors. NASA CR-54530. Allison EDR-4575. 1967.

15. Crouse, J. E. Personal communication. 1978.

16. Johnson, I. A., and Bullock, R. O., eds. Aerodynamic Design of Axial-Flow Compressors. NASA SP-36. 1965.

17. Hearsey, R. M. A Computer Program for Axial Compressor Design. Volume I. Theory, Descriptions, and Users Instructions. Technical Report AFAPL-TR-73-66, Volume I. 1973.

18. Hearsey, R. M. A Computer Program for Axial Compressor Design. Volume II. Program listing and Program Use Example. Technical Report AFAPL-TR-73-66, Volume II. 1973.